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ABSTRACT

The design and performance of an on-line counter hodoscope for the study of high-energy photons and photon-induced reactions are discussed.

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The design and performance of an on-line counter hodoscope for the study of high-energy protons from photon-induced reactions are discussed.

1. DESIGN CONSIDERATIONS AND INSTRUMENTATION

Despite two decades of intensive work, the need for accurate cross-section data on photon-induced interactions in the energy region between 400 and 1000 MeV is as great as ever. As a first step in obtaining such data, we have developed an on-line counter hodoscope for the detection of protons of energies between 100 and 300 MeV. In this paper, we wish to present a brief description of the hodoscope and discuss some points which have arisen in analysing the data collected.

The basic design parameters of the hodoscope were determined by the following considerations:

1. The beam intensity at the Lund electron synchrotron was rather low (about $4.5 \cdot 10^{10}$ electrons per s) at the time the hodoscope was projected. The data-collecting rate was expected to be limited by the available beam intensity to about one event per second. The on-line data transfer system can handle one event per machine pulse.
2. The fact that background reactions can contribute to the observed counting rate often limits the use of single-arm detection systems to the upper part of the photon spectrum. When this is not possible, more complicated coincidence arrangements must be used to enable the desired reaction to be studied clearly.
3. We wished to develop a simple, flexible system

which could be extended if opportunity offered. This implied that we should use a single-arm detector and work near the end of the bremsstrahlung spectrum. Study of the kinematics of several elementary processes (e.g. $\gamma + p \rightarrow p + \pi^0$, $\gamma + d \rightarrow p + n$) suggested that a range of about 75 MeV in proton energy would adequately cover the usable photon energy interval. Calculations of counting-rates suggested that a proton energy resolution of about 8 MeV would give reasonable photon energy resolutions and running times.

The layout of the hodoscope is shown in Figure 1. The entire counter assembly is mounted in an enclosure screened by thick lead walls to reduce the intense background present during the machine output pulse. A preliminary collimation of the particle flux from the target is made by a lead insert with three 7 cm diameter holes.

The hodoscope can be thought of as being in two sections. In the forward part, the 1/4" thick scintillators are used to determine if an event should be recorded for subsequent analysis. In these scintillators, the biases are set so that all protons stopping in scintillator 18 are recorded. In the 1/8" thick rear scintillators (9-18), the range of the particle is determined by recording the pattern of counters fired by an event satisfying the trigger criteria. The biases in these counters are set on the lower slope of the peak from relativistic

which could be extended if opportunity offered. This implied that we should use a silicon detector and work near the end of the bremsstrahlung spectrum. Study of the kinematics of several elementary processes (e.g. $\gamma + p \rightarrow p + \pi^0$, $\gamma + n \rightarrow p + \pi^-$) suggested that a range of about 75 MeV for proton energy would adequately cover the useful photon energy interval. Calculations of counting rates suggested that a photon energy resolution of about 5 MeV would give reasonable photon energy resolutions and counting times.

The layout of the hodoscope is shown in Figure 1. The entire counter assembly is mounted in an aluminum vacuum chamber. The hodoscope is made of three 1/8" thick lead plates with three 1/8" diameter holes. A preliminary estimation of the particle flux from the background process indicated that the output noise level would be acceptable. The hodoscope can be thought of as being in two sections. In the forward part, the 1/8" thick scintillators are used to determine if an event should be recorded for subsequent analysis. In these scintillators, the particles are seen that all protons stopping in scintillators are recorded. In the 1/8" thick rear scintillators (9-18), the range of the particle is determined by recording the pattern of counters fired by an event satisfying the trigger criteria. The pattern in these counters

particles which pass through the entire counter assembly, in an attempt to equalize the uncertainty in the widths of the various bins due to the non-zero scintillator biases. Counters 3, 8 and 19 are anti-coincidence counters. The first is a Plexiglass Cerenkov counter 5 cm thick, which removes relativistic particles from the incident flux. The second is a scintillator with three holes which define the solid angle of the particle beam at the hodoscope, each being millisterradians. The use of a lead collimator to define solid angle is perhaps more frequent. However, there can be uncertainties introduced by the finite target size. It was hoped that better definition of the effective solid angle could be obtained with a thin scintillator in anti-coincidence than by the use of a thick lead collimator. Counter number 19 defines the maximum range of events in the hodoscope. The anti-coincidence signals used to veto events are, wherever possible, formed as a coincidence between the signals from the anti-coincidence counters and the counters on either side of them, to minimize the loss of events due to random pulses in the anti-counters. Apart from this, the electronic coupling used is conventional and merits no special description.

Aluminium absorbers of thicknesses chosen so as to cover the desired range of proton energies with the correct resolution are placed between the counters. Typical ranges of energies used have been 109 to 176 MeV and

162 to 234 MeV.

As can be seen from Figure 1, three pieces of scintillator material (Pilot B) are mounted on a common light-guide in the range-part of the hodoscope. We have elsewhere reported on this¹⁾.

Data are collected simultaneously at three angles spaced at intervals of six degrees. Bits defining the angle of an event are taken from counters 71-73 which are mounted on separate photo-tubes and cover one angle each. The arrangement described is rather economical in its requirements, requiring only twenty photo-multipliers to count ten energy bins at each of three angles.

Coincidence times of about 20 ns have been used in the measurements. The anti-coincidence pulses are about 50 ns long and the final gate pulse which opens the various data units is also about 50 ns,

The on-line computer is an IBM 1800 with 24 K 16-bit core memory used with the IBM 1800 TSX V3 operating system to permit time-sharing.

Transfers of data to the computer are initiated after two types of events: a) an event satisfying the requirements in the hodoscope (2 $\bar{3}$ 4 5 7 $\bar{8}$ $\bar{19}$) and b) a signal recording the end of a dose on the integrator coupled to a quantameter. The data sent to the computer after each event include some control words to check the data transfer, information from ADCs about the pulse-heights in various scintillators, and words defining the angle and hodoscope pattern.

At the end of a dose, these data are transferred together with the readings of some thirty scalers which record the single rates and various coincidence frequencies. The computer makes various consistency checks, updates several registers recording the more important statistics of the data-collecting and stores the data prior to writing on an IBM 2401 magnetic tape unit.

Since we were unable to obtain a commercial interface for transferring data between the IBM 1800 and the (mainly) LeCroy units used for the instrumentation of the hodoscope, we had to develop our own. The unit has groups of three interrupts of different degrees of priority. The highest level is used for the quantameter dose interrupt and the next level for the event interrupt. The logical construction of the unit was somewhat complicated by the fact that the only output signal which could be obtained from the computer was the ready signal. However, by suitable design, it was possible to ensure that the unit had a memory so that when two interrupts (one of them a quantameter dose) occurred simultaneously, the second was stored until the data-transfer initiated by the first was completed. In extensive tests, this unit was found to be very reliable.

Gating was used to ensure that the ready signal from the computer was well-separated in time from the output pulse from the machine, to prevent loss of events due to

the fact that units are inhibited during a read-out cycle.

In general, during data collection, the intensity was kept at a level such that 90% of all events were transmitted for analysis.

2. PERFORMANCE OF THE HODOSCOPE

As stated earlier three separate classes of information are collected after each event: angle-bits, the hodoscope patterns and pulse-height information.

Angle-bits

Analysis of the angle-bit information has not presented difficulties. Usually only about 0.3% of all events have not been analysable due to the firing of two angle counters simultaneously. This number is consistent with the expected occurrence of random events.

Hodoscope pattern

The classification of hodoscope patterns has presented considerably more difficulty. It is obvious that the passage of a particle through the hodoscope should be signalled by a pattern of consecutive ones followed by consecutive zeroes. In data-collecting runs on carbon about 30% and with hydrogen about 10% of all events have not been of this type.

To permit the classification of these patterns, the following observations have been used:

Near the end of their range, protons ionize heavily giving large pulses and so it is not very probable that

they are not detected.

Study of the experimental material shows that the great majority of the unclassifiable patterns are of the type in which a row of consecutive ones is followed after at least one zero by one extra bit.

Calculation of the number of random coincidences on the basis of the observed counting rates indicated that, e.g. in hydrogen, about 1% of all events would be lost because of random pulses in each bin. The sum of all the bins of the hodoscope (10%) is in agreement with the figure observed.

Furthermore, the probability of occurrence of events such as e.g. 11 1 0 0 1 0 0 1 0 was compatible with the frequency expected on the basis of the frequencies of the separate patterns 1 1 1 0 0 1 0 0 0 0 and 1 1 1 0 0 0 0 0 1 0 .

On the basis of these considerations, the criterion developed for the classification of hodoscope patterns was that if one zero was immediately followed by two or more consecutive ones, it was filled out. For two consecutive zeroes, at least three immediately following consecutive ones were required. If there was only one extra bit, it was eliminated.

Separate runs were made to check the correctness of this procedure. Detailed analysis of these runs indicated that it was satisfactory. About 99% of the anomalous

patterns are adequately accounted for.

Measurements taken over a wide range of beam intensities were in good agreement.

It should be noted that, since classification of bin number precedes the application of pulse-height criteria, the figures quoted here refer to all events as collected, without any further discrimination. The numbers are reduced by at least a factor of two if protons only are considered. In particular, events with missing bits then become very rare.

Pulse height spectra

Typical undiscriminated pulse-height spectra are shown in Figure 2 for one of the forward bins. The raw spectra in a non-coincidence measurement are heavily contaminated with electrons and pions. In our case, the electronic selection of events is such that the lower-energy bins in any one configuration comprise up to 70% pions and electrons. The effects on the spectra of biassing in different counters during the off-line analysis are shown in Figure 3 and Figure 4 for a front and a rear counter respectively. A considerable tail of low-mass particles is still present in these spectra. Figure 5 shows the results of biassing simultaneously in 3 counters. The low-mass tail is further reduced but is never wholly eliminated. Table 1 shows how the number of events in the proton region varies with different bias conditions. The most effective

discrimination is found in the counters towards the end of the range. The front counters appear to be relatively inefficient in separating protons from other particles.

The question of how to extract the correct number of protons from the final spectra has been studied in considerable detail using different methods in an attempt to obtain clean distributions. It appears however that due to limited statistics the various methods of peak-fitting do not give more satisfactory results than are given by a manual evaluation.

Results of the manual subtraction used are estimated to be accurate to 2% at energies below 200 MeV but only to 10% for 300 MeV protons, at which energies the pion and proton peaks in forward counters overlap strongly, reducing the effective number of bias possibility.

3. CALCULATION OF HODOSCOPE PARAMETERS

Among the parameters of interest in determining cross-sections are:

- a) the proton energy distribution in the various bins
- b) the width of proton energies accepted in each bin
- c) the transmission coefficients for protons as a function of energy
- d) corrections for Coulomb scattering in the absorbers and
- e) the effective solid angle

Only a) - d) are treated here: e) is treated separately later in section 5 . The methods of determining the hodoscope parameters used in the present work are a continuation of methods developed earlier²⁾. These are to be described in another context and so only the most relevant details will be summarized here.

The proton energy distributions in the various bins were determined by tracing the paths of protons of integral values of energy through the hodoscope until they either stopped or entered the anti-counter (19). This was performed for twenty equally-spaced planes in the target and histograms of the distributions obtained. When needed, the mean value of proton energy could readily be obtained from these histograms. In these calculations, the proton energy spectrum was assumed to be flat, since earlier calculations had indicated that the difference between this choice of spectrum and the actual experimental distribution is very small.

The effective width of proton energies recorded on a bin (which is needed for non-two-body final-state interactions) was obtained by a similar procedure. In this case, the paths of protons just reaching the front and rear planes of an absorber were traced back to a plane in the target and the difference in their energies calculated. This was repeated for 40 planes in the target and the average calculated.

There are unavoidable differences in bias among the scintillators and their thicknesses are not constant to

better than 10% . The estimated error in the evaluation of this parameter is therefore about 3%.

Calculation of the effective proton transmission coefficient and the Coulomb scattering coefficient require knowledge of the energy losses in each absorber in the hodoscope. These were calculated for two cases, viz protons just reaching the front and back planes of the absorber, the target thickness being taken to be half the geometric value (carbon) or half the calculated mean trajectory length in the target (hydrogen). The corrections were obtained by weighting these results of these two cases in the ratio 2:1 to allow for the shape of the experimental proton energy spectrum.

Knowing the incident and exit energies for each absorber, the transmission coefficients were obtained as the product of the individual coefficients of each element from tables of the transmission coefficients as a function of absorber type and proton energy. The values so obtained are comparable with those reported by Measday and Richard-Serre³⁾.

The calculations of Coulomb scattering followed the methods of Sternheimer⁴⁾. The average energy in each absorber was taken as the average of the incident and exit energies and the absorber was assumed to be located at its geometric mid-point. Since there is double collimation of the proton flux, first by a lead collimator at the entrance and then by counter 8, two separate contributions have to be evaluated. Both are discussed by Sternheimer. In general the reduction of the flux due to

1. The first part of the paper is devoted to the study of the properties of the function $f(x)$ defined by the equation

$$f(x) = \int_0^x \frac{1}{1+t^2} dt$$

It is well known that this function is the arctangent function, i.e. $f(x) = \arctan x$. The first part of the paper is devoted to the study of the properties of this function. In particular, it is shown that the function is odd, i.e. $f(-x) = -f(x)$, and that it is bounded on any finite interval. The second part of the paper is devoted to the study of the properties of the function $f(x)$ on the interval $(-\infty, \infty)$. It is shown that the function is strictly increasing and that it has horizontal asymptotes at $y = -\frac{\pi}{2}$ and $y = \frac{\pi}{2}$. The third part of the paper is devoted to the study of the properties of the function $f(x)$ on the interval $(-\infty, \infty)$. It is shown that the function is strictly increasing and that it has horizontal asymptotes at $y = -\frac{\pi}{2}$ and $y = \frac{\pi}{2}$.

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the lead collimator was about 2% and the correction for scattering in the rear somewhat smaller. Owing, however, to the many approximations made in the calculation, there can be an error of about 1% in the final results.

5. EVALUATION OF THE DIFFERENTIAL CROSS-SECTION

The fundamental relation connecting the number of protons obtained from the counting rate in the detector and the differential cross-section can generally be written as:

$$N_p(E_p, \theta_p^{\text{lab}}) = \int \dots \int \frac{d\sigma}{d\Omega}(k, \theta_p^{\text{cm}}) \frac{1}{f} n(k, E_o) I_t^n n_t d\Omega dk dV_t$$

Here, I_t^n is the normalized spatial intensity distribution of the photon beam, the normalization being

$$I_t^n = \frac{I_t}{\int_{S_t} I_t dS_t}$$

where I_t is the spatial intensity distribution.

$N_p(E_p, \theta_p^{\text{lab}})$ Number of protons counted per one equivalent quanta in the bremsstrahlung beam. Denoted by N_p in the following.

E_p Kinetic energy of the protons in lab system

θ_p^{lab} Proton lab angle

$\frac{d\sigma}{d\Omega}(k, \theta_p^{\text{cm}})$ Differential cross section

k Photon lab energy

θ_p^{cm} Proton cm angle

f Factor for transforming the differential cross-section from the lab to the cm system

F_Q	Quantameter constant ($4.53 \cdot 10^{18}$ MeV/As)
E_o	Bremsstrahlung end point energy
$n(k, E_o)$	Bremsstrahlung spectrum
n_t	Number of target atoms per cm^3
V_t	Irradiated volume of the target
S_t	Cross section of the beam perpendicular to its direction
Ω	Solid angle

The number of equivalent quanta Q in the incident bremsstrahlung beam is given by

$$Q = \frac{U}{E_o}$$

where U the total energy content in the beam

$$U = \int_0^{E_o} n(k, E_o) k dk$$

The calculation of the differential cross-section involves thus the evaluation of a six-fold integral over kinematical and geometrical variables depending on one another in a complicated way. A complete calculation can therefore only be performed for reactions in which the kinematics are uniquely determined, i.e. two-body final state reactions. We treat these cases first.

To evaluate the integral we transform it into a product of mean values over the respective integration intervals. This procedure involves an approximation because one has to assume that the differential cross-section which we

are calculating may be approximated by its mean value in the photon energy acceptance interval Δk and the angular acceptance interval $\Delta\theta^{\text{cm}}$, defined by the reaction kinematics and the experimental set-up. With this limitation in mind, the differential cross-section can be written explicitly in the following way in terms of the different experimental parameters:

$$\frac{d\sigma}{d\Omega}(k, \theta_p^{\text{cm}}) = \frac{N_p}{N_{\text{ph}}} \frac{1}{t_{\text{eff}}} \frac{1}{\Omega_{\text{eff}}} \frac{1}{n_t} f$$

Here, N_{ph} is the number of photons per equivalent quantum in the bremsstrahlung beam which can produce protons in the energy interval studied, t_{eff} is the effective target thickness in the beam direction and is given by

$$t_{\text{eff}} = \int_{S_t} I_t^n t_t dS_t$$

where t_t is the thickness of the target element parallel to the incident beam direction. Ω_{eff} is the effective solid angle of the experimental set-up.

It is calculated from:

$$\Omega_{\text{eff}} = \frac{\int_{V_t} I_t^n \Omega' dV_t}{\int_{V_t} I_t^n dV_t}$$

where Ω' is the solid angle element subtended at the detector from the volume element dV_t in the target.

The number of photons, N_{ph} , is calculated from the

bremsstrahlung spectrum and the photon energy acceptance distribution. The latter is obtained by folding together the angular acceptance distribution, defined by the geometry of the set-up, with the proton energy acceptance distribution taking reaction kinematics into consideration. In Figure 6 the relative contributions from the two terms are shown for a typical case. If $p_{\text{acc}}(k)$ is the photon energy acceptance distribution, N_{ph} is given by

$$N_{\text{ph}} = \frac{E_0}{U p_{\text{acc}}(k)_{\text{max}}} \int_{k_{\text{min}}}^{E_0} n(k, E_0) p_{\text{acc}}(k) dk$$

where $p_{\text{acc}}(k)_{\text{max}}$ is the maximum value of the photon energy acceptance distribution.

For the bremsstrahlung spectrum a Schiff form⁵⁾ is assumed.

The techniques used for evaluation of the integrals are described elsewhere⁶⁾. For this reason, the method is described only briefly here. The integrals are transformed into finite sums in which each term gives the contribution to the sum from one volume element in the target volume or one surface element on the detector surface. Summations are then performed by scanning the entire target volume and (or) the entire detector surface element by element and adding the contributions. This numerical method of evaluating the integrals has the advantage that empirically-determined input data describing the experimental configuration can be used. The accuracy of the final result is then only limited by that of the input data.

In reactions in which the kinematics are not uniquely determined, e.g. photoproton emission from carbon, the fundamental integral cannot be evaluated. In these cases the differential cross-section is conventionally normalized against unit proton energy and number of equivalent quanta in the beam instead of the actual number of photons in the energy interval of the bremsstrahlung beam accepted. It is calculated from

$$\frac{1}{Q} \frac{d^2\sigma}{d\Omega dE_p} = \frac{N_p}{\Delta E_p} \frac{1}{t_{\text{eff}}} \frac{1}{\Omega_{\text{eff}}} \frac{1}{n_t}$$

where ΔE_p is the width of the proton energy bin accepted.

6. CONCLUSIONS

The performance of the on-line counter hodoscope described above has been found to be satisfactory. The main experimental difficulties have been to determine the effective widths of the bins, the values of which are, in general, not known to better than about 3%, and the number of protons in a given spectrum.

Extensive tests of the hodoscope have been made with a carbon target. Many data on the emission of photo-protons have been obtained at this laboratory using a different counter hodoscope³⁾. A comparison between the old and new data sets is shown in Figure 7. The data obtained in the present work have not been corrected for background which is about 3-5% in the angular region around 40°. With this in mind, the agreement is seen to be good.

A fuller report listing of these carbon cross-sections will be circulated later.

The hodoscope is currently being used for measurements of π^0 -production from hydrogen, with some emphasis on the photon energy about 500 MeV, where few data are at present available. The results of these measurements will be submitted later for publication.

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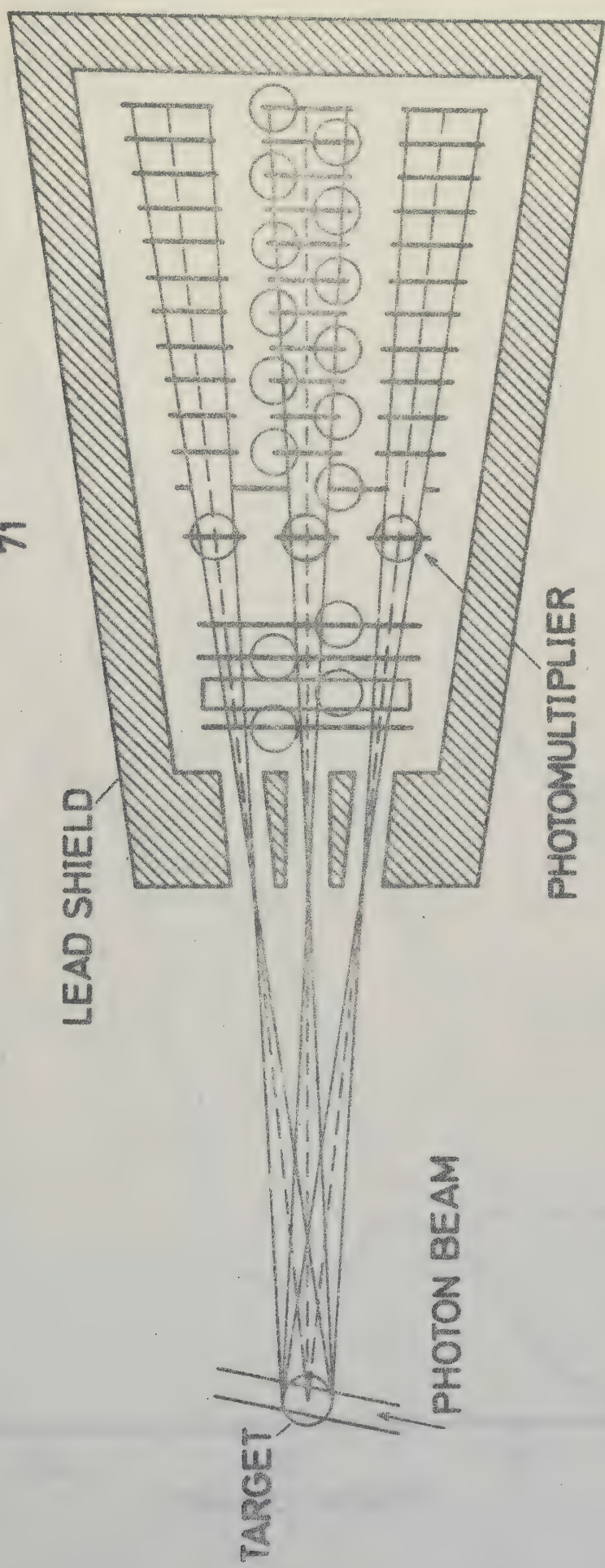
T A B L E 1

Off-line discri- minator condition	Number of particles				
	TOTAL	In P r o t o n peak			
		I	II	III	IV
None (Figure 2)	5846				
DI (Figure 3)	1726	(1726)	1452	1394	1290
DII	1601	1452	(1601)	1433	1300
DIII	1534	1410	1433	(1534)	1290
DIV (Figure 4)	1417	1276	1289	1290	(1417)
DI+DII	1452	(1452)	(1452)	1398	1281
DI+DII+DIII (Figure 5)	1398	(1398)	(1398)	(1398)	1276
DI+DII+DIII+DIV	1265	(1265)	(1265)	(1265)	(1265)
DIII+DIV	1290	1268	1280	(1290)	(1290)
FINAL NUMBER OF PROTONS EVALUATED MANUALLY					1245

FIGURE CAPTIONS

- Figure 1 The general lay-out of the on-line counter hodoscope.
- Figure 2 Typical undiscriminated pulse-height spectra. The curves denoted I, II, III and IV are spectra recorded in counters 2, 4, 5 and 9 respectively for particles stopping in the absorber between the counters 12 and 13.
- Figure 3 Pulse-height spectra for off-line biasing of one front counter. In the figure arrows show the bias levels used in each counter.
- Figure 4 Pulse-height spectra for off-line biasing of one rear counter.
- Figure 5 Pulse-height spectra for off-line biasing 3 counters simultaneously.
- Figure 6 Curve A shows the proton lab angle acceptance distribution and curve B the proton lab energy acceptance distribution. The three curves C, D and E showing the photon energy acceptance distribution for the reaction $\gamma p \rightarrow p\pi^0$ are calculated by using the distribution A and $E_p = 110.5$ MeV, $\Delta E_p^{\text{lab}} = 1$ MeV for C, distribution B and $\theta_p^{\text{lab}} = 28.4^\circ$, $\Delta\theta_p^{\text{lab}} = 0.1^\circ$ for D and distributions A and B for E. For the experimental configuration used in the calculations we assumed incident beam radius = 1.65 cm, target radius = 3.25 cm, detector radius = 3.00 cm and target-detector distance = 130.0 cm. The mean photon energy and the widths of the distributions are $\bar{E}_\gamma = 375.8$ MeV and $\Delta E_\gamma = 11.2$ MeV, $\bar{E}_\gamma = 374.2$ MeV and $\Delta E_\gamma = 18.9$ MeV and $\bar{E}_\gamma = 374.3$ MeV and $\Delta E_\gamma = 21.7$ MeV for C, D and E respectively.
- Figure 7 Differential cross-section for emission of photo-protons of energies between 140 and 220 MeV from carbon irradiated with bremsstrahlung of 400 MeV maximum energy.

COUNTER 2 . . . 5 73 72 8 71 19



0 10 20 30 40 50 CM

Fig.1

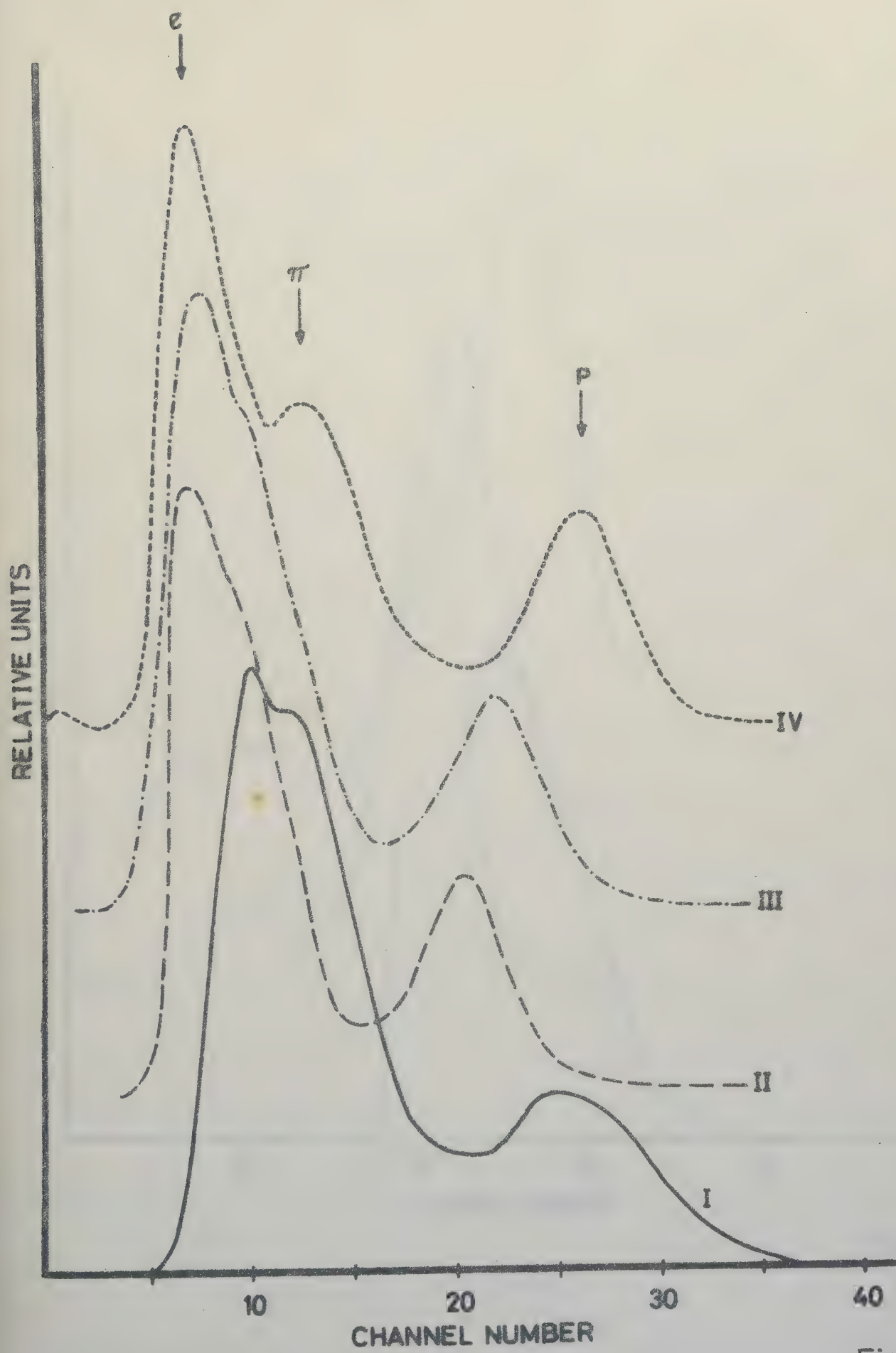


Fig.2

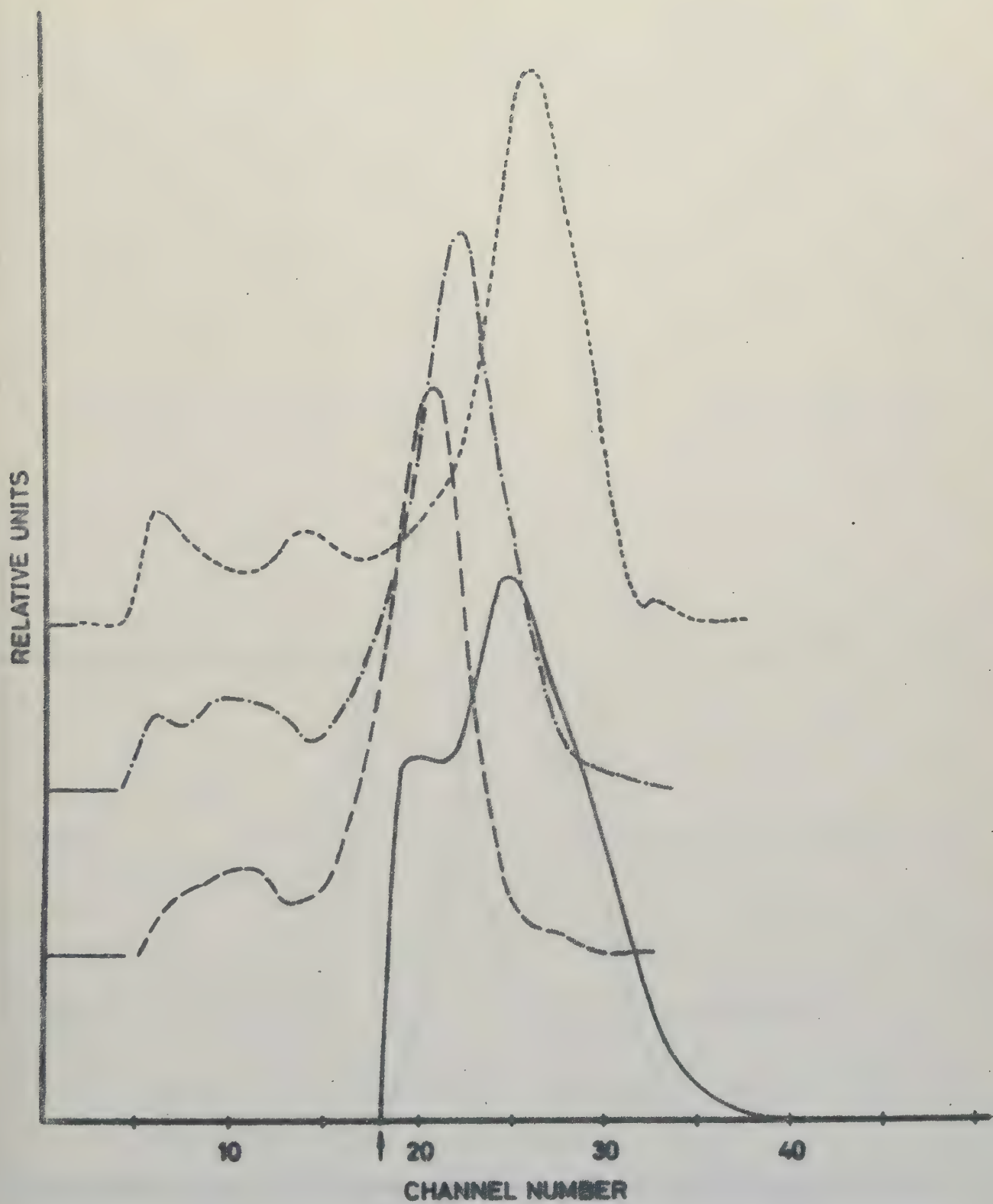


Fig.3

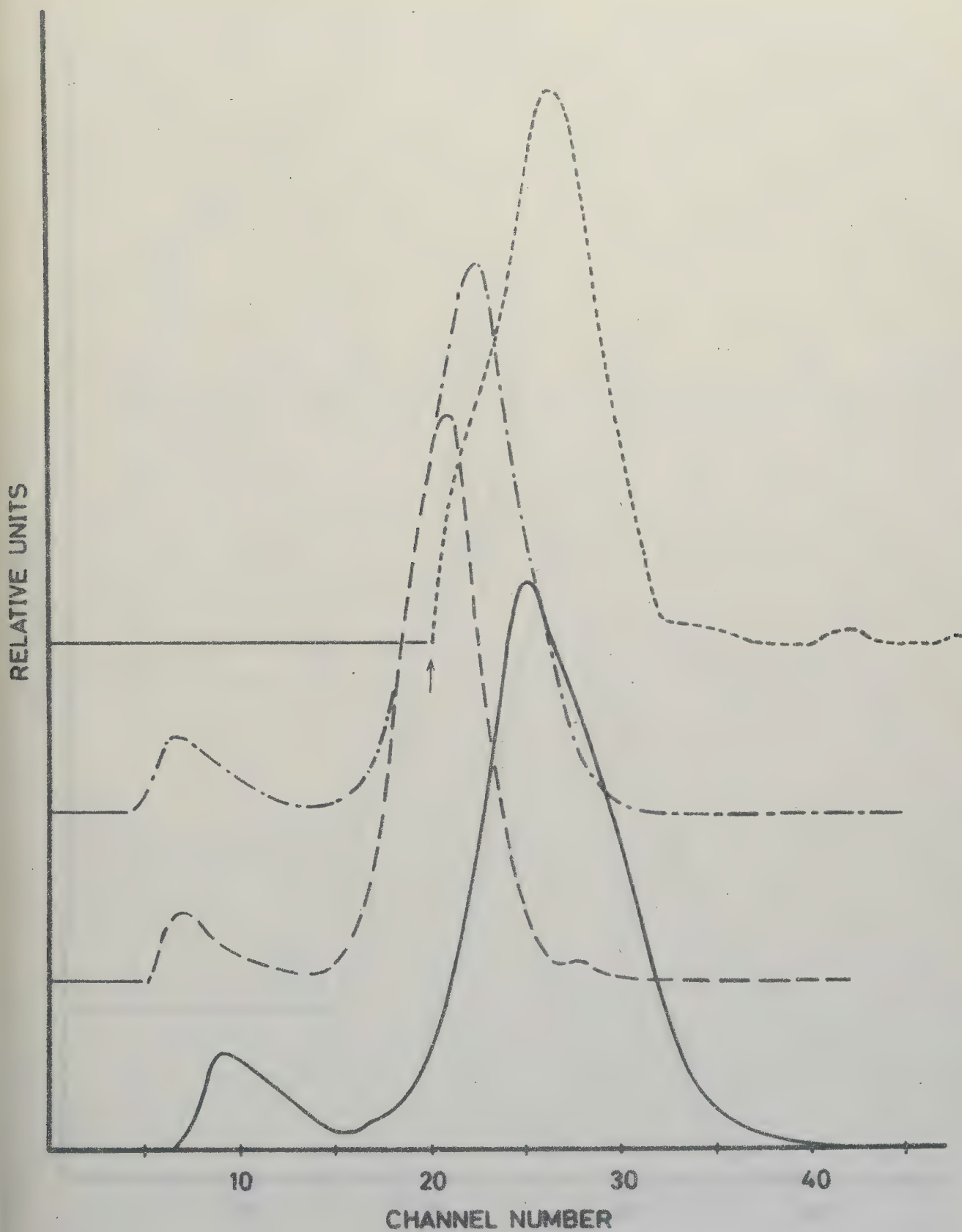


Fig.4

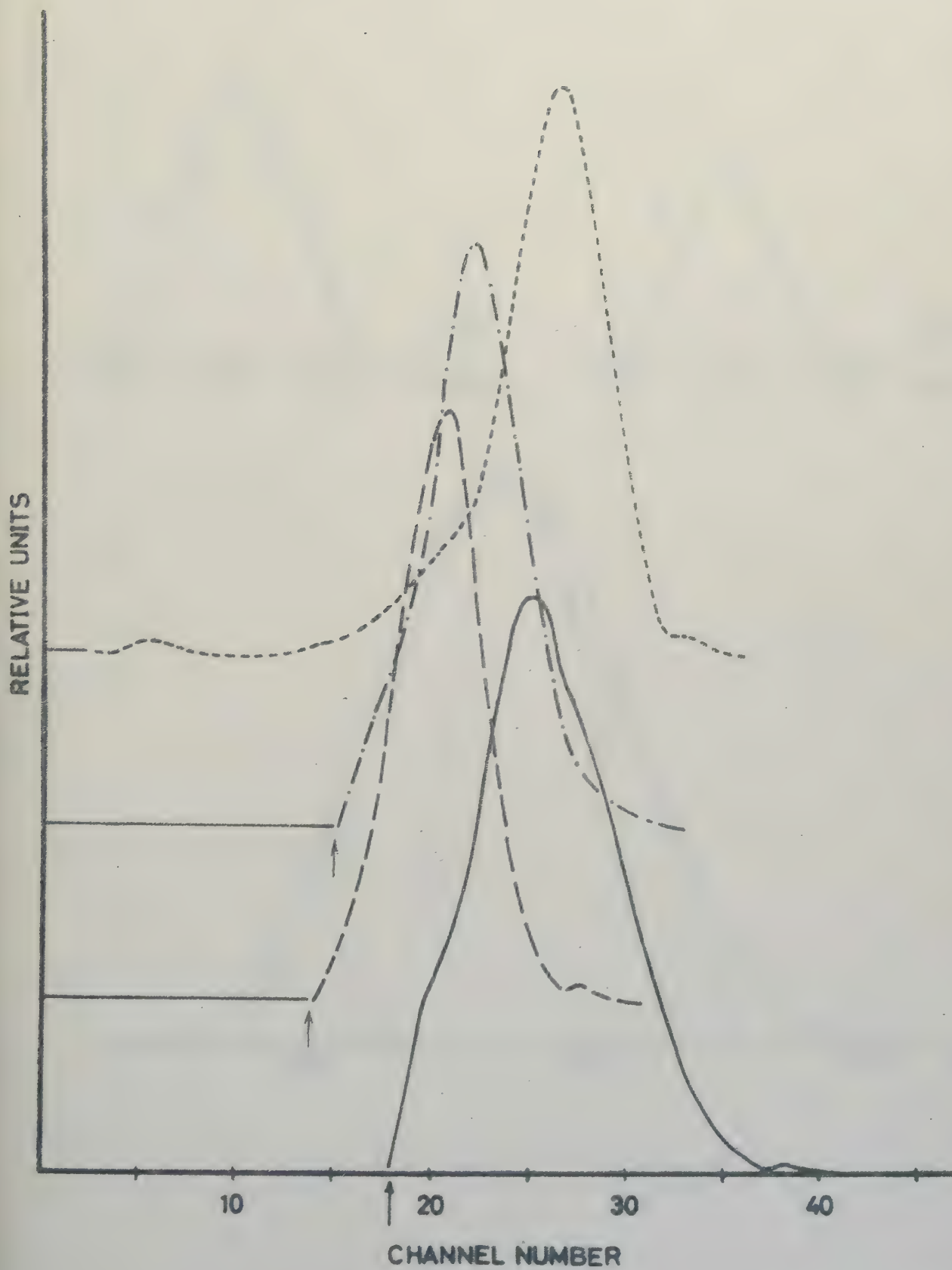


Fig.5

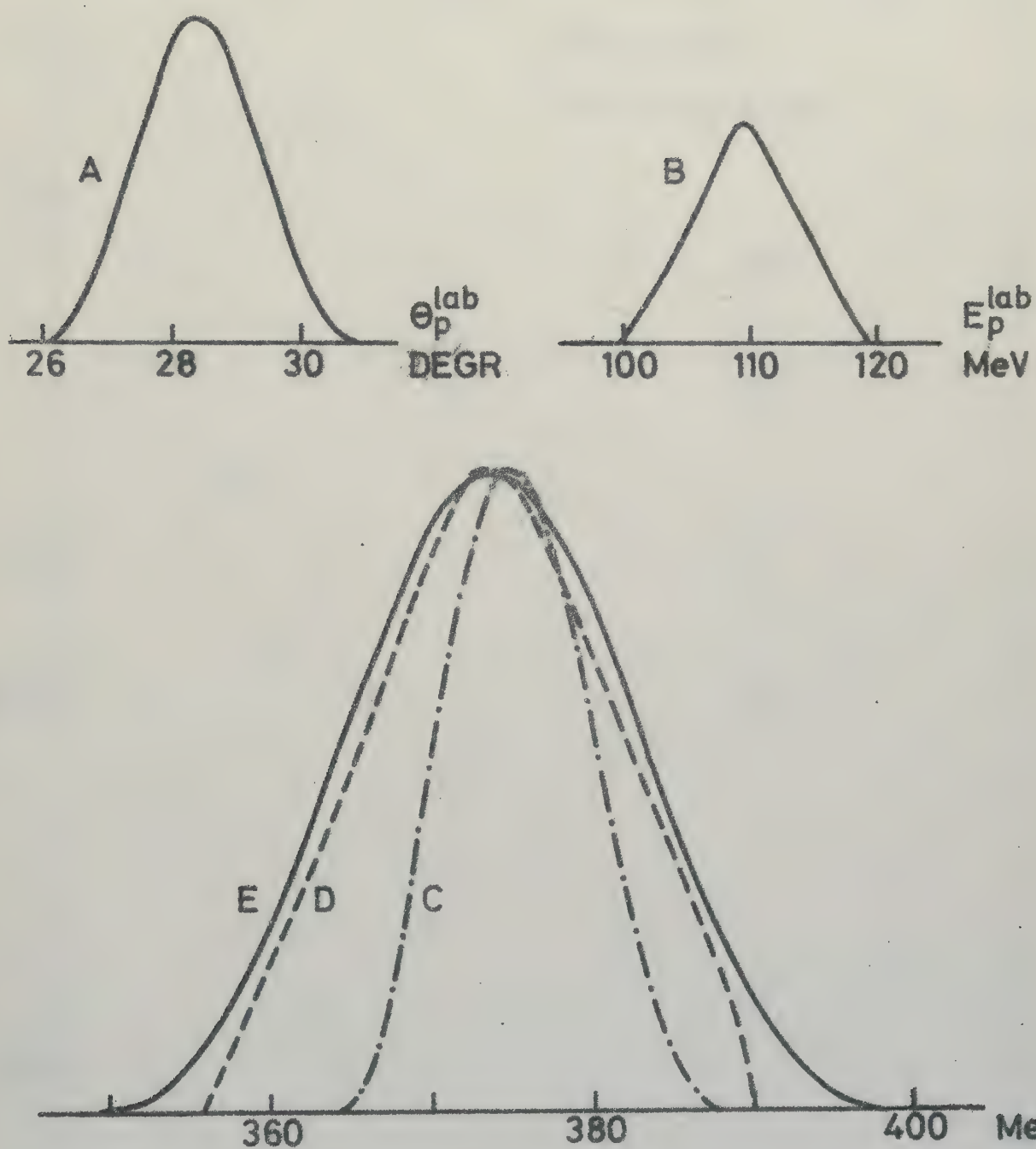


Fig.6

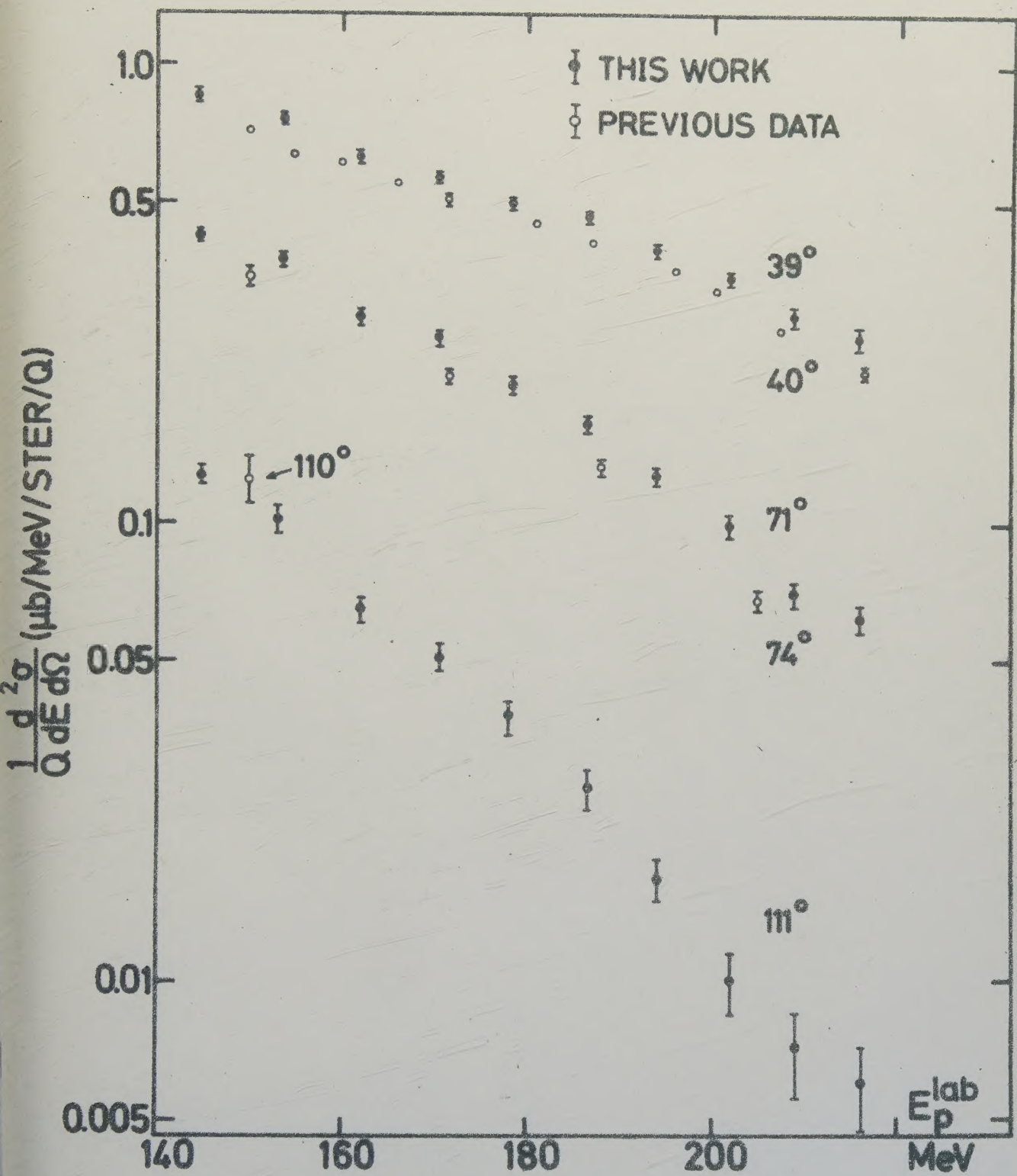


Fig.7

